

Imaging Spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

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ABSTRACT

Imaging spectroscopy is of growing interest as a new approach to **Earth remote sensing**. The **Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)** was the first imaging sensor to measure the solar reflected spectrum from 400 to 2500 nm at 10 nm intervals. The calibration accuracy and signal-to-noise of AVIRIS remain unique. The AVIRIS system as well as the science research and applications have evolved significantly in recent years. The initial design and upgraded characteristics of the AVIRIS system are described in terms of the sensor, calibration, data system and flight operation. This update on the characteristics of AVIRIS provides the context for the science research and applications that use AVIRIS data acquired in the past several years. Recent science research and applications are reviewed spanning investigations of atmospheric correction, ecology and vegetation, geology and soils, inland and coastal waters, the atmosphere, snow and ice hydrology, biomass burning, environmental hazards, satellite simulation and calibration, commercial applications, spectral algorithms, urban and human infrastructure, as well as modeling.

1.0 INTRODUCTION

Spectroscopy is used in the laboratory in the disciplines of physics, chemistry and biology to investigate material properties based on the interaction of electromagnetic radiation with matter. Imaging spectroscopy in the solar reflected spectrum was conceived for the same objective, but from the Earth looking and regional perspective (Figure 1). Molecules and particles of the land, water and atmosphere environments interact with solar energy in the 400 to 2500 nm spectral region through absorption, reflection and scattering processes. Imaging spectrometers in the solar reflected spectrum are developed to measure spectra as images in some or all of this portion of the spectrum. These spectral measurements are used to determine constituent composition through the physics and chemistry of spectroscopy for science research and applications over the regional scale of the image.

To pursue the objective of imaging spectroscopy, the Jet Propulsion Laboratory proposed to design and develop the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) in 1983. AVIRIS first measured spectral images in 1987 and was the first imaging spectrometer to measure the solar reflected spectrum from 400 to 2500 nm (Figure 2). AVIRIS measures upwelling radiance through 224 contiguous spectral channels at 10 nm intervals across the spectrum. These radiance spectra are measured as images of 11 km width and up to 800 km length with 20 m spatial resolution. AVIRIS spectral images are acquired from the Q-bay of a NASA ER-2 aircraft from an altitude of 20,000 m. The spectral, radiometric, and spatial calibration of AVIRIS is determined in laboratory and monitored inflight each year. More than 4 terabytes of AVIRIS data have been acquired and the requested data calibrated and distributed to investigators since the initial flights.

AVIRIS has measured spectral images for science research and applications in every year since 1987. More than 250 papers and abstracts have been written for the AVIRIS workshops (Vane, 1988, Green 1990a; Green 1991a; Green 1992a; Green 1993a; Green 1995a; Green; 1996a). The workshop documents and additional information are maintained on the AVIRIS website (<http://makalu.jpl.nasa.gov/AVIRIS.html>). In the past ten years, there have been an equivalent number of AVIRIS papers written for other workshops, symposia, and conferences. A previous special journal issue related to AVIRIS has been published (Vane 1993). There are additional AVIRIS related articles and papers throughout the remote sensing literature.

The AVIRIS system has been upgraded and improved in a continuous effort to meet the requirements of investigators using AVIRIS spectral images for science research and applications. These improvements have been directed towards the AVIRIS sensor, calibration, data system, and flight operations. In parallel with the sensor, the science research and applications pursued with AVIRIS has diversified and evolved. This paper describes the characteristics and recent improvements to the AVIRIS system. The paper also reviews a range of science research and applications results and objectives pursued with AVIRIS and provides a context for the accompanying articles in this journal special issue.

2.0 SENSOR

The AVIRIS sensor receives white light in the foreoptics, disperses the light into the spectrum, converts the photons to electrons, amplifies the signal, digitize the signal and records the data to high density tape. The major subsystems of the sensor are the: scan mirror, foreoptics, spectrometers, detectors, onboard calibrator, and electronic signal chain (Figure 3). The initial design contained many opportunities for improvements with advances in technology. The initial design, improvements and the signal path through AVIRIS are described.

The upwelling radiance arriving at AVIRIS in flight (Figure 4) enters through a 2.45 cm thick hatch window in the ER-2 aircraft. This hatch window is composed of water free fused silica and has an average transmittance of better than 0.95 across the spectrum. An anti reflection coating was applied to the hatch window to further improve transmittance. Light arriving from the hatch window passes through the AVIRIS aperture door and is reflected into the foreoptics from an oscillating whiskbroom scan mirror. The aperture door is closed to protect the scan mirror and foreoptics and automatically opened only when spectral images are being measured. The door replaces an aperture window that reduced throughput and introduced a small amount of scattered light into the AVIRIS foreoptics. The scan mirror is silver coated and triangular in cross section with two primary facets giving a 10 by 20 cm equivalent area. The oscillating scan drive sweeps the mirror across the active 30 degree field of view of the Earth at a rate of 12 hertz. Significant engineering effort was required to develop a scan drive to sweep linearly across the 30 degree field-of-view and then fly back at nearly twice the speed to start the next imaging scan (Miller 1987). The AVIRIS scan drive approaches 70 percent efficiency. The great advantage of a whiskbroom scanner is that the light for every spatial element passes through the same path of the optical system. This gives exceptional uniformity for the 614 cross track spatial samples in each AVIRIS image scan line.

From the scan mirror the light enters into the foreoptics which has an instantaneous field of view (IFOV) of 1 milliradian. In the foreoptics, the light is reflected from five mirror surfaces and recombined from the double faceted scan mirror. The aluminum mirrors are silver coated to give high reflectivity across the AVIRIS spectral range. An elliptical mirror is used to match the IFOV with the 0.45 numerical aperture of optical fibers at the exit of the foreoptics. A mechanical shutter is

located at the exit of the foreoptics in front of the fiber optics. This shutter closes for the non imaging portion of each scan line to allow measurement of the dark signal levels. Sixty-four samples of dark signal are averaged for each scan line. Averaging is required to suppress the single sample noise in the dark signal.

Light leaving the fore optics is focused on four 200 micron diameter optical fibers with 0.45 numerical apertures. These fibers transmit the light to one each of the four spectrometers that are used to cover the spectral range from 400 to 2500 nm. Silica glass fibers are used for the range from 400 to 1300 nm. Zirconium fluoride glass fibers with a beryllium fluoride cladding are used from 1300 to 2500 nm. These high numerical aperture exotic glass fibers were specifically developed for AVIRIS and were the first of their kind. However, these fibers are easily damaged by water condensation and water vapor. Several measures were required to isolate the fibers from ambient humidity of the AVIRIS operational environment. These included the placement of sapphire windows on the fiber ends and the development of a dry air unit to provide a high flow source of warm dry air for use in humid environments. The use of optical fibers is essential for AVIRIS and enables the independent alignment of the foreoptics and spectrometers as well as the compact packaging required for the ER-2 aircraft.

In the spectrometer subsystem, light from each of the optical fibers enters a different spectrometer covering a portion of the AVIRIS spectral range. The A, B, C, and D spectrometers cover the nominal spectral ranges of 400 to 700 nm, 700 to 1300 nm, 1300 to 1900 nm, and 1900 to 2500 nm respectively. These spectrometers are off-axes Schmidt design. White light from the optical fiber enters each spectrometer with a cone angle of 45 degrees. The light is collimated by a spherical mirror onto a reflection grating where the light is diffracted into the spectrum. The reflection gratings are convex with a correction surface shape unique to each spectrometer. The groove spacing and blaze angle of each reflection grating is optimized for the spectral range of each spectrometer. From the grating the dispersed light reflects from the spherical mirror and is focused on the detector array. The 0.45 numerical aperture of the AVIRIS spectrometers caused significant optical design and implementation challenges (Macenka and Chrisp 1987). However, because the solar reflected spectrum is broken into four spectral ranges, the design of each spectrometer could be optimized for the specific spectral range.

The AVIRIS spectrometers are aligned and calibrated in the laboratory at ambient room temperature. At altitude, the Q-bay of the ER-2 may reach temperatures of -10 degrees Celsius. To allow alignment in the laboratory and maintain the performance of the spectrometers in flight, the spectrometers are heated and insulated. In the current improved design, a series of eight heater circuits and temperature probes are used to control the temperature of each spectrometer. A 32 loop thermal control system is used to maintain the temperature of the four AVIRIS spectrometers slightly above laboratory alignment temperatures at all times. Thermal control of the spectrometers is required to maintain radiometric and spectral stability of the AVIRIS that is required for calibration.

Light dispersed into the spectrum by the AVIRIS spectrometers is measured by the detector subsystem. At the exit to each spectrometer, light enters a cryogenic dewar that holds the a linear detector array. In front of each detector array is a field flattening lens and a blocking filter. The field flattener rectifies the dispersed image onto the detector array. For each spectrometer a unique blocking filter is used to suppress light of wavelengths not appropriate to the spectrometer. In the D spectrometer a carefully specified linear variable blocking filter is used to limit the wavelengths of light for each element in the detector array. This specialized filter reduces the noise resulting from photons emitted by the spectrometer in the 1900 to 2500 nm spectral range. For the A spectrometer, a 32 element silicon detector array that has a blue enhanced response is

used. The detector elements are 200 by 200 microns and operated with the dewar at ambient spectrometer temperature. The B, C and D spectrometer each have 64 element arrays of indium antimonide detectors. The dimensions of the detectors in the B and C arrays are 200 by 200 microns and the quantum efficiency is optimized for the spectral regions. The detector elements in the D spectrometer array are 214 by 500 microns in dimension. These larger detectors are used to capture photons not arriving in the nominal 200 by 200 micron area of the D spectrometer focal plane. The B, C and D detector arrays are operated at near 77 degrees K. The temperature is controlled by the boil off valve attached to the liquid nitrogen filled cryogenic dewars. The detector arrays in each spectrometer receive the spectrally dispersed photons and convert them to electrons. The electrons are read off the array elements by buffered direct injection circuits that are specifically developed for AVIRIS. New detectors and a new multiplexor design were installed in AVIRIS in 1995. This upgrade resulted in more than a factor of two increase in signal-to-noise. Each array is read out every 87 microseconds to coincide with the motion of the scan mirror through one spatial resolution element. A timing delay in the detector read out is used to align the spectrum from the A, B, C and D spectrometer to the same spatial sample. The signals from the detectors are amplified and digitized by the electronics attached to the dewar. The measured AVIRIS signal is digitized at 12 bits and recorded as 224 channels of data (Figure 5).

A critical subsystem required to achieve the calibration objective of AVIRIS is the onboard calibrator. This subsystem has been upgraded a number of times (Chrien et al. 1995a). Data from the onboard calibrator are measured at the beginning and end of each image flight line. The signal source for the onboard calibrator is a 10 watt quartz halogen lamp rated for 5000 hours. The intensity of signal from the lamp is stabilized by a silicon detector feedback circuit. The current to the lamp is continuously adjusted to keep the signal measured by the onboard calibrator silicon detector constant. A narrow band filter centered at 543.5 nm wavelength is placed in front of the detector to limit the detector response to a spectral range of temperature insensitivity. To further improve stability, the temperature of the entire onboard calibrator is regulated to 40 degrees Celsius with a dedicated temperature controller. The light from the bulb is passed through a balancing filter to deliver appropriate signal levels across the AVIRIS spectral range. The filtered light is focused on the end of a bundle of optical fibers. The light is transmitted through the optical fibers to the back of shutter that is also used to measure dark signal. During onboard calibrator data acquisition the AVIRIS spectrometers measure the light from back of the shutter. A high signal, two spectral signals and a dark signal (Figure 6) measurement are acquired for each onboard calibrator sequence. The signal from the onboard calibrator is used in the calibration of all AVIRIS data and to monitor the spectral and radiometric performance of AVIRIS through the entire flight season.

The AVIRIS electronic signal chain controls the digitized spectra, the engineering data, the navigation data, and the overall operation of AVIRIS. The digitized spectra from each spectrometer are passed into AVIRIS high speed data buffer. In the buffer, data from the A, B, C and D spectrometers are placed in spectral order. Synchronization and count values are placed in the data stream to identify each spectrum and scan line. Temperatures and voltages as well as other housekeeping signals from the AVIRIS sensor are encoded. Navigation data from a global positioning system sensor and an inertial navigation system are integrated into the data stream. The average dark signal measured with the foreoptics shutter closed during the return scan is added to the data stream. This buffered data stream is passed to the high density tape recorder at a rate of 20.4 megabits per second. The tape recorder holds up to 10.4 gigabytes or 60 minutes of data. Orchestration of the acquisition AVIRIS spectral images and ancillary data for each flightline is performed by the AVIRIS computer. Because the ER-2 is a

single person aircraft, the AVIRIS system is required to be nearly autonomous and collect sufficient monitoring data to allow diagnosis of a wide range of possible problems that arise in flight.

In each year typically eight months are reserved for acquisition of AVIRIS spectral images for science research and applications. In the remaining four months, effort is invested towards maintaining and upgrading the performance of AVIRIS. Maintenance objectives are designated based on evidence of marginal performance of a subsystem or subsystem component. Upgrades efforts are based on a balance of investigator requirements and the constraints of the AVIRIS design. Fortunately, the initial AVIRIS design has been well suited to a series of significant upgrades (Chrien et al. 1990, Chrien 1992, Chrien et al. 1993a, Sarture et al. 1995). AVIRIS is a sophisticated and complex optical sensor system involving a number of major subsystems, components and characteristics (Table 1). Taken together these result in the AVIRIS data characteristics (Table 2).

3.0 CALIBRATION

AVIRIS is spectrally, radiometrically and spatially calibrated in the laboratory before and after each flight season (Chrien et al. 1990, Chrien et al. 1995b). At the beginning, middle and end of the flight season, the calibration of AVIRIS is validated in flight onboard the ER-2. Before and after each AVIRIS flight line, measurements are acquired from the onboard calibrator. This nested set of calibration measurements allows the AVIRIS calibration requirement to be achieved. AVIRIS data are required to be spectrally, radiometrically and spatially calibrated in order to: derive physical parameters from measured radiance; compare data acquired from different regions and from different times; compare and analyze AVIRIS spectra with data acquired by other instruments; and compare and analyze data with results from computer models.

In the laboratory AVIRIS is spectrally calibrated with a computer controlled three grating monochromator that covers the solar reflected spectral range. The monochromator is calibrated to the emission lines of low pressure mercury and krypton vapor lamps. Spectral orders of the emission lines are used to cover the full range monochromator. These emission lines are the AVIRIS spectral calibration standard. Following calibration of the monochromator, a quartz halogen lamp is used to illuminate the entrance slit of the monochromator. Light of 1.0 nm spectral width is passed from the monochromator to a collimator that fills the AVIRIS aperture. The monochromator is automatically scanned across each grating at 0.5 nm spectral steps. Simultaneously the measured AVIRIS signal is recorded. The calibrated monochromator input and the AVIRIS measured signals are analyzed with a set of computer programs to determine the spectral positions, response functions, and uncertainties of the 224 AVIRIS spectral channels (Figure 7). This spectral calibration process was recently automated and may be completed less than 48 hours for the 224 spectral channels. Historically, AVIRIS spectral calibration took more than a week and required a number of interpolation steps.

The primary AVIRIS radiometric calibration standard is 1000 watt quartz halogen lamp with irradiance traced to the National Institutes of Standards and Technology. The lamp is powered by a regulated power supply of known current and voltage. A new approach has been developed to calibrate AVIRIS with this radiometric standard. A fixture has been constructed that holds the lamp a known distance from a reflectance standard. This fixture also positions the illuminated panel in the AVIRIS field of view and overfills the field of view. Advantages of this approach are that no transfer spectrometers or radiometers are required and no secondary radiometric source is needed. AVIRIS views radiance that arrives from the standard lamp by way of

the standard reflectance panel. Use of this method requires careful baffling of scattered light away from the panel as well as knowledge of the bi-directional reflectance properties of the standard panel. Radius and cosine attenuation of the light reflected from the panel must be compensated as well. The ratio of the known radiance incident at AVIRIS from the panel and the digitized numbers reported by AVIRIS are used to calculate the radiometric calibration coefficients (Figure 8). In addition to being used in the laboratory, this fixture is used at the ER-2 operation site to monitor and improve absolute radiometric calibration through the flight season. To measure and calibrate the radiometric uniformity across the AVIRIS field of view, a one meter diameter integrating sphere with 30 cm aperture is used in the laboratory. An absolute calibration of the integrating sphere is not required. Two additional radiometric calibration standards are being introduced to further improve AVIRIS absolute radiometric calibration. A quantum efficient detector is being used to assess the absolute radiometric calibration accuracy in the visible portion of the spectrum. A metal freezing point radiation source is being integrated into the radiometric calibration procedures to provide an additional reference in the 1000 to 2500 nm portion of the spectrum.

The radiometric precision or signal-to-noise of AVIRIS is determined in the laboratory. The average and standard deviation of 3000 dark signal spectra are used to determine the signal chain noise. The average and standard deviation of an additional 3000 spectra from the radiometric calibration target are used to calculate the signal dependent photon sampling noise. These two noise components are used to calculate the signal-to-noise for the AVIRIS reference radiance (Figure 9). The AVIRIS reference radiance was specified in the original AVIRIS proposal to NASA as the radiance from a 0.5 reflectance target illuminated at 23.5 degree at sea level with the mid latitude standard atmosphere. The current signal-to-noise of AVIRIS is vastly improved over that in 1987 as well as over that in 1994.

The spatial calibration of AVIRIS is measured periodically in the laboratory in a manner analogous to spectral calibration (Chrien et al. 1993b). A quartz halogen lamp is used to illuminate a narrow slit. The illuminated slit is scanned across the focus of a collimator that overfills the AVIRIS aperture. The signal measured by AVIRIS as the slit is scanned is used to determine the spatial response function (Figure 10). Both the cross-track and along track spatial response functions are measured. The spatial calibration of AVIRIS is important for investigations examining targets with dimensions near or below the AVIRIS spatial resolution.

Field experiments are held at the beginning, middle, and end of the flight season to validate the calibration of AVIRIS in flight from the Q-bay of the ER-2. The initial years of AVIRIS operations demonstrated that a laboratory calibration alone was not sufficient to assure calibration of AVIRIS in flight (Conel et al. 1988, Green et al. 1988). At this time, the laboratory calibrations did not accurately describe the performance of AVIRIS in the flight operations environment. In flight calibration validation experiments were developed to assess the calibration of AVIRIS in the Q-bay of the ER-2 (Green et al. 1990b, Green et al. 1996b). These experiments acquire in situ measurements of the surface and atmosphere at a homogeneous dry lake bed calibration target at the time of AVIRIS spectral image acquisition. The in situ measurements are used to constrain the MODTRAN radiative transfer code (Berk et al. 1989, Anderson et al. 1995) and predict the radiance incident at AVIRIS. The predicted radiance is compared to the AVIRIS measured radiance traced to the laboratory calibration with the onboard calibrator. The level of agreement between the MODTRAN predicted and the AVIRIS measured radiance is reported to validate AVIRIS calibration in flight (Figure 11). Since 1995, the average absolute agreement between the predicted and measured radiance has been better than 96 percent. The residual disagreement must be partitioned amongst the field

measurements, the MODTRAN code, the calibration standards, and the AVIRIS sensor. These experiments are essential to confirm the accuracy of AVIRIS calibration in flight. Science research and applications data sets are only measured in flight.

4.0 DATA SYSTEM

The AVIRIS data system contains the computer hardware and software for calibration analysis, performance analysis, trend analysis, archiving, quicklook generation, data calibration and data distribution. The AVIRIS data system is UNIX based with software written in standard C and FORTRAN. Prior to 1996, the AVIRIS data system was based on 4 mm archive tapes accessed by hand, a complex relational database, and a monolith data processing program for all years of AVIRIS data. Under this system AVIRIS scenes (140 megabytes) could be delivered at an average rate of 6 per day. In 1996 the AVIRIS data system software and hardware had become complicated to the point that the modifications to allow calibration and distribution of 1996 data took almost the entire year. In November 1996 the decision was made to redesign the complete AVIRIS hardware and software system. The most critical component of the new data system hardware is a 4 terabyte automated mass storage system. From the perspective of the software and operating system this mass storage device operates as a slow 4 terabyte disk. The AVIRIS software functionality was redesigned and rewritten as a set of small software modules not dependent on a database. To bypass the database, all file names are based on the date, tape, power cycle, and flight line of the acquired AVIRIS data. This uniquely identifies every data set and is immediately informative. The software modules are divided into four classes, calibration analysis, engineering analysis, routine AVIRIS processing, and experimental AVIRIS algorithms.

AVIRIS data calibration analysis uses a set of software modules that support reduction of laboratory and field calibration data. The radiometric calibration modules allow reduction and analysis of the radiometric calibration measurements and radiometric standards. These modules sort and distill the more than 3 million AVIRIS spectra acquired during calibration and generate the radiometric calibration coefficients and uncertainties. A set of spectral calibration modules perform the same function for determination of the AVIRIS spectral channel positions, response functions and uncertainties. Spatial calibration software modules are used to determine the spatial calibration characteristics of AVIRIS. Software modules have also been developed to derive surface and atmosphere parameters from field measurement. These are used for constraint of the radiative transfer code for the validation of AVIRIS calibration in flight. AVIRIS calibration software modules are specialized, interactive, flexible, and require expert knowledge of the calibration process.

The engineering analysis software for AVIRIS consists of a set of software modules that provide access to the uncalibrated AVIRIS data as well as the engineering and navigation data recorded by AVIRIS. Following acquisition of each AVIRIS high density data tape an engineering performance evaluation program module is run. This program reports a selected set of noise, signal, temperature, and scan characteristics of the AVIRIS data. These characteristics are automatically evaluated with a series of pass/fail thresholds. The results are automatically emailed to the lead members of the AVIRIS team. During science flight operations, the performance evaluation software is run within 48 hours following each flight. Rigorous performance evaluation has exposed a number of potential or incipient problems before they propagated into the flight data. Trend analysis is a second essential engineering software module. This program extracts information for all the AVIRIS data sets acquired in a year and formats them for statistical analysis and graphical plotting. Parameters such as the onboard calibrator high signal, dark signal, noise, engineering temperatures, and voltages are compiled. The trend analysis module is

a powerful tool to assess the quality of AVIRIS data and to explore for subsystems and components that are in need of maintenance. As required, additional specialized engineering software modules are developed to address specific engineering questions.

AVIRIS routine processing modules allow archiving, generation of quicklooks, calibration and distribution of spectral image data. In the archiving software modules, data from the high density tape is transferred to hard disk as an exact copy of the 12 bit digitized data. A second module expands the 12 bit data to 16 bit integers on disk and generates a header file with specific information about the AVIRIS data set. These 16 bit AVIRIS spectral images are copied to the automated mass storage device. Following archiving of AVIRIS data a quicklook image is generated. The quicklook image is a single AVIRIS channel stretched at 512 line intervals. The quicklook is placed on the AVIRIS web site along with an index that contains site names and location information. The calibration module retrieves the 16 bit data from the automated mass storage device and applies the calibration algorithms to the data. Calibrated AVIRIS data are written to hard disk with all the associated calibration, engineering and navigation information as separate files. The distribution program is the final module. This program reads the calibrated AVIRIS data and divides the flight line into a series of 512 scan line image scenes. The scenes and ancillary files are written to a standard UNIX TAR file (Table 3). The TAR file is copied to tape and sent to the requesting investigator. The new AVIRIS calibration and distribution software and hardware have sufficient performance to allow automatic calibration and distribution of all measured AVIRIS data to the investigators. This procedure was adopted in 1997 and all measured AVIRIS data were delivered.

With the installation of new hardware and development of new AVIRIS software modules a number of experimental algorithms are enabled. For example, a four module automated reflectance inversion algorithm has been implemented. The code accepts information for the AVIRIS navigation file and performs a series of radiative transfer calculation to model a range of possible atmospheric condition with variations in water vapor and aerosols. The navigation data is used to access the surface elevation data from a global topographic data set. As second module convolves the radiative transfer calculated spectra to the AVIRIS spectral characteristics and reduces the calculated spectra to an analytical function based on the water vapor and aerosol parameters. The third module performs a non linear least squares spectral fit between the AVIRIS measured spectra and the modeled spectra to derive the water vapor for each spatial element in the AVIRIS image. The final module performs a full inversion of the measured radiance to surface. This software is currently run for selected reflectance inversion validation data sets. Another experimental software module accesses the automated mass storage system to reprocess an entire flight season of AVIRIS data to test for cirrus cloud contamination. The algorithm generates a quicklook image from the 1380 nm AVIRIS channel where cirrus clouds are strongly expressed. An experimental software module was developed to examine every AVIRIS spectrum measured during the 1995 deployment to Brazil. The algorithm tests for the presence of actively burning fire and reports the location and spectrum. Additional broadly posed questions are possible now that an entire flight season of AVIRIS data is accessible through the automated mass storage system.

The recent vast improvement in the AVIRIS data system arises from the modular software design and automated mass storage technology. Since data distribution began on the new system, more than 4500 AVIRIS scenes or 630 gigabytes have been distributed to investigators. A peak throughput of 180 calibrated AVIRIS scenes was achieved in a single day. As part of the migration to the new data system, all AVIRIS data measured from 1992 to present are being re archived and made available in the new format. The automated mass storage basis of the system will enable easy migration to new mass storage

technology in the future. Also, the entire AVIRIS data set may be replicated for long term data storage at an alternate location. The new AVIRIS data system is being used as the basis for proposed spaceborne imaging spectrometers.

5.0 FLIGHT OPERATIONS

The objective of AVIRIS is to measure imaging spectroscopy data for science research and applications. This objective is only achieved when AVIRIS is operating from the Q-bay of the NASA ER-2 aircraft (Table 4). For typically eight months of each year, AVIRIS is deployed and collecting data sets with the ER-2. Following laboratory calibration, AVIRIS is shipped to the ER-2 operation site with a complete set of ground support equipment. The first flight following a period of engineering maintenance is dedicated an in flight calibration validation experiment. Once the first flight is complete and AVIRIS performance validated, the flight season commences. In the weeks and months preceding shipping, a data base of approved investigators is reviewed by the AVIRIS experiment coordinator and the ER-2 pilots. The list of approved AVIRIS data acquisitions is maintained on the AVIRIS web site. Investigators are contacted and requested to review the planned flight lines. On the day prior to each planned flight day, the possible data acquisitions are determined and reviewed at a 1 PM meeting. Nominal targets for the following day are selected based on the investigator requests, predicted weather, aircraft status, and AVIRIS status. Following the 1 PM meeting, investigators are informed of the plans for acquisition of their data.

On the morning of the flight, four hours prior to takeoff the preflight preparation and checkout of AVIRIS begins. The AVIRIS sensor is uploaded into the ER-2 aircraft, if necessary. Ground power is applied to the sensor through the aircraft and the cryogenic detector dewars are filled with liquid nitrogen. A tape is inserted in the high density tape recorder and series of commands are issued to AVIRIS from the ground support computer. These commands format the tape and collect signals from the onboard calibrator and other subsystems of AVIRIS. Voltages, currents, temperatures and signal levels are checked to confirm AVIRIS is operating within specification. A test data set is recorded to confirm the end-to-end operation of AVIRIS. In this period the regional weather is reviewed and the final decision is made for data acquisitions. Investigators are contacted by the AVIRIS experiment coordinator. Data from one to four investigators may be acquired on a single flight. In the hour prior to takeoff the pilot enters the ER-2 and the engine is started to provide aircraft power. On the runway immediately prior to takeoff AVIRIS is turned on and the pilot acquires a small AVIRIS data set to confirm sensor operation.

Once airborne, the pilot proceeds to the planned acquisition sites. Typically, AVIRIS data sets are acquired from one latitude and longitude point to another as specified by the investigator. The pilot notes the location and time of each flight line as well as the cloud and haze conditions. An AVIRIS flight may last 6.5 hours and range more that 2000 km from the operations base. As the pilot returns to the operations base a final data set is acquired at altitude to record the performance of AVIRIS at the end of the mission. Once on the ground, the AVIRIS warm/dry air unit is connected to the ER-2 to eliminate the risk of water condensation damage. After warm up, the ground computer is connected to AVIRIS, the post flight performance evaluated, and the flight tape ejected. The AVIRIS experiment coordinator reviews the flight with the pilot and completes a flight log that relates the record cycles on the tape to the data sets acquired. The flight log and high density tape are express shipped to the AVIRIS data system. Within 48 hour of acquisition the flight data are evaluated and the results reported to the experiment coordinator and the pilot.

These flight operation procedures are repeated through the eight month data acquisition period. During the flight season AVIRIS is usually deployed to two or three bases of operation with the ER-2. These bases are typically east coast and mid continent. Each deployment entails significant shipping and coordination logistics. AVIRIS has deployed outside the conterminous United States to Europe, Alaska and Brazil.

6.0 RESEARCH AND APPLICATIONS

AVIRIS has measured spectral images for research and applications since the late 1980's. Both the calibration and signal-to-noise of AVIRIS has improved each year since the initial flights. In parallel to the upgrades to the AVIRIS system, the understanding of the spectral characteristics of materials in the land, water, and atmosphere environments has improved. The improved sensor system characteristics and understanding of the spectrum, have enabled a wide range of science research and applications based on spectral images measured by AVIRIS. A review of some of these investigations with AVIRIS spectral images is given. The number and diversity of investigations continues to grow each year.

6.1 ATMOSPHERIC CORRECTION

AVIRIS measures the total upwelling spectral radiance at 20 km altitude above the surface. The majority of investigations using AVIRIS data for research and applications are pursuing questions that are expressed in the reflectance of the surface. Strategies, algorithms, and approaches for atmospheric correction and derivation of surface reflectance are essential for these investigations. The empirical line atmospheric correction was one of first methods applied to AVIRIS data (Elvidge 1988). For this method, the reflectance of two or more targets in the AVIRIS data set are independently measured. A linear relationship is determined between the AVIRIS measurement and the known reflectance of the targets. This relationship is used to transform the entire AVIRIS data set to reflectance. Strengths of this approach are that absolute radiometric calibration of the sensor data is not required. Drawbacks of this approach are the need for concurrent in situ spectral reflectance measurements and the failure to account for lateral and temporal variations in the atmosphere.

To move beyond the need for in situ measurements, radiative transfer atmospheric correction algorithms have been developed. These algorithms derive the spatial distribution of water vapor, aerosols, and other atmospheric constituents from the AVIRIS spectra. With these atmospheric constraints an inversion from radiance to reflectance for each AVIRIS spectrum is performed (Green 1990c, Gao et al. 1991a, Gao et al. 1993, Green et al. 1993b, Zagolski, et al. 1995, Leprieur et al. 1995, Gaddis et al. 1996, Staenz et al. 1996). Several of these methods have been compared in research studies (Farrand et al. 1994, Clark et al. 1995). With these radiative transfer based methods, there are differences between the radiative transfer calculations and the calibrated AVIRIS spectra. These differences cause residual spectral artifacts in the derived reflectance. A number of strategies have been developed to suppress these artifacts. One method requires independent knowledge of the reflectance of at least one target in the AVIRIS data set (Clark et al. 1995). Work is continuing to bring the radiative transfer calculations and AVIRIS measurements into closer agreement. The advantage of these radiative transfer reflectance inversion methods is that in situ surface measurements are not required.

6.2 ECOLOGY AND VEGETATION

Ecology and the study of terrestrial vegetation are important objectives for research with AVIRIS spectral images. Leaf water, chlorophyll, ancillary pigments, cellulose, lignin, and other constituents in conjunction with the leaf and canopy structure combine to produce the reflectance of vegetation as measured by AVIRIS. Leaf water is an important vegetation constituent with absorption bands at five locations in the solar reflected spectrum. AVIRIS has been used to measure the expressed leaf water in vegetation (Green et al. 1991b, Gao et al. 1991b, Roberts et al. 1993, Gao et al. 1995a, Ustin et al. 1998). The non photosynthetic fraction of vegetation was not previously measured with remote sensing methods. Analyses with AVIRIS using the full spectrum has enabled the separation and measurement of the nonphotosynthetic of fraction vegetation (Roberts et al. 1990, Ustin et al. 1992, Roberts et al. 1993, Gao et al. 1994). Remote sensing determined canopy chemistry may allow measurement and monitoring of changes in plant function with changes in the atmosphere and the climate. A number of research investigations have focused on the use of AVIRIS spectral images for canopy chemistry (Martin et al. 1993, Gastelluetcheorry et al. 1995, Kupiec et al. 1995, Martin et al. 1997, Curran et al. 1997). Canopy chemistry investigations have benefited from the high signal-to-noise of recent AVIRIS data. AVIRIS spectral measurements have been used to determine ecological patterns of use and productivity in vegetated regions (Gamon et al. 1992, Ustin et al. 1996, Wessman et al. 1997, Roberts et al. 1997). Detection of trace quantities of vegetation has been pursued with AVIRIS (Elvidge 1990, Chen et al. 1992, Elvidge et al. 1993), as well as assessment of vegetation fraction (Sabol et al. 1993, Garciaaharo et al. 1996), and measures of canopy closure (Staenz et al. 1993). The identification of vegetation type and in some cases identification of species has been demonstrated with calibrated and high signal-to-noise AVIRIS spectral images (Martin et al. 1998 and Roberts et al. 1998). Research is continuing to understand the relationship between vegetation spectral reflectance and leaf chemistry and structure as well as plant and canopy architecture. Understanding of these relationships is essential for expansion and quantification of the ecological research and applications based on calibrated AVIRIS spectral images.

6.3 GEOLOGY AND SOILS

The application of AVIRIS spectra to geology and soil investigations is based on the large number of minerals with unique spectral absorption features in the solar reflected spectrum. AVIRIS has been used to determine the point, local and regional distribution of minerals for a range geology and soil science investigations. A group of minerals with strong molecular absorption features are associated with hydrothermal alteration. These hydrothermal minerals have been mapped in a range of investigations (Carrere et al. 1988, Hook et al. 1990, Swayze et al. 1992, Sommer et al. 1993, Boardman et al. 1996, Ferrand et al. 1997, Beratan et al. 1997) with AVIRIS. AVIRIS spectra have also been used to map ammonium minerals (Baugh et al. 1995, Baugh et al. 1998). Alkaline and carbonatite rock types have been mapped with AVIRIS (Rowen et al. 1995, Bowers et al. 1996). Carbonate, clay, iron oxide minerals found in sedimentary rocks enable spectroscopic mapping of the units and sub units with AVIRIS (Boardman et al. 1991, Clark et al. 1992, Lang et al. 1996). Evaporite minerals express spectral absorption features in the AVIRIS spectral range that have been used to map these sedimentary units (Crowley 1993). An interesting application of imaging spectroscopy to active igneous geology is the measurement of the temperature of exposed lava and volcanic hot spots (Oppenheimer et al. 1993). The radiance emitted by the hot lava is expressed in the AVIRIS spectrum. As with rocks, the mineral absorption and scattering characteristics of soils are expressed in the AVIRIS spectral ranges. Absorption features in soils tend to be subtle due to particle size, scattering and coating effects. AVIRIS spectra have been used to map the distribution and relationship between soil sequences and other surface materials (Fox et al. 1990, Fischer et al. 1991, Mustard 1993, Palaciosorueta et al. 1996). The improved signal-to-noise of AVIRIS supports mapping more subtly expressed minerals as well as mapping several minerals expressed within a single AVIRIS spectrum of

the surface. AVIRIS spectral images are suited to any geology or soil research or application question that is posed in terms of the distribution of minerals exposed at the surface.

6.4 COASTAL AND INLAND WATERS

The number of absorbing and scattering components found in the coastal ocean, lakes and rivers supports the use of spectroscopy to isolate and measure the constituents of these environments. These constituents include: chlorophyll, a wide range of planktonic species, dissolved organics, suspended sediments with local and distant sources, bottom composition, submerged aquatic vegetation, etc. AVIRIS spectra and in situ measurements have been used to investigate the distribution of constituents in lake systems (Melack et al. 1992, Jaquet et al. 1994, Novo et al. 1995). In the coastal environment AVIRIS spectra have been used to investigate coastal ocean reflectance (Pilorz et al. 1990), algal blooms (Richardson et al. 1994), sediment plumes (Carder et al. 1993) and bathymetry (Sandidge et al. 1998). The increased signal-to-noise and absolute calibration of AVIRIS in the 400 to 1000 nm portion of the spectrum is supporting new investigations in the coastal and inland water environments.

6.5 THE ATMOSPHERE

Constituents of the atmosphere are strongly expressing the solar reflected spectra measured by AVIRIS. These constituents include water vapor, clouds, aerosols, ozone and other atmospheric gases. Water vapor is of interest as a critical component of the atmosphere and as the primary absorber across the AVIRIS spectral range. A range of algorithms and approaches have been developed for derivation and analysis of water vapor (Conel, et al. 1988, Green et al. 1991b, Gao et al. 1991b, Bruegge et al. 1992, Schlepfer et al. 1998). In general, these algorithms assess the strength of the 940 nm water vapor absorption and relate the strength to the total column water abundance. AVIRIS derived water vapor is an essential input to model based reflectance inversion and is of interest for understanding the spatial and temporal distribution of this atmospheric component (Green et al. 1995).

Cirrus clouds play an important role in the global energy balance and are an often undetected confounding factor in remote sensing data. AVIRIS spectral images in the strong water vapor absorptions at 1380 and 1850 nm provide a new approach to detect the presence and distribution of cirrus clouds (Gao et al. 1992, Gao et al. 1995b, Hutchison et al. 1996). In addition, algorithms have been developed to assess and compensate for the effects of cirrus clouds in AVIRIS spectral images (van den Bosch et al. 1993). Non cirrus cloud fraction and cloud shadow analyses have been pursued with AVIRIS (Gao et al. 1990, Kou, et al. 1990, Berendes et al. 1991, Feind et al. 1995). Recently, the MODTRAN radiative transfer code has been improved to more accurately model the expression of clouds in the solar reflected spectrum (Berk et al. 1998). Measurement of aerosols is of interest for understanding impacts on the local and global atmosphere. Knowledge or estimation of aerosol is required for atmospheric correction of imaging spectroscopy and other remote sensing data. Aerosols are expressed in AVIRIS spectral range and have been the topic of investigation (Isakov et al. 1996, Kaufman et al. 1997). Whether focused on the surface or the atmosphere, all investigations with AVIRIS must account for the atmosphere. Research in this discipline continues to expand and be strongly relevant.

6.6 SNOW AND ICE HYDROLOGY

Properties of snow and ice expressed in the AVIRIS spectral range are: fractional cover, grainsize, surface liquid water content, impurities, and shallow depth. Snow grainsize is required to model the albedo of snow. Snow albedo plays a significant roll in the regional and global energy balance. Derivation of snow grainsize has been pursued with AVIRIS spectra (Nolin et al. 1993). Liquid water in melting snow has been shown to modify the solar reflected spectrum of snow (Green et al. 1995c). Radiative transfer model based methods have been pursued to derive the snow grainsize and liquid water content simultaneously from spectra measured by AVIRIS (Green et al. 1996c). Advanced methods of spectral mixture analysis have been developed and applied to derive grainsize (Painter et al. 1995, Painter et al. 1998). These new methods account for the non linear expression of grainsize in the reflected spectrum of snow. Research and analysis continue to improve and validate derivations of snow properties from AVIRIS measured spectra.

6.7 BIOMASS BURNING

Characteristics of the fuel, fire process, combustion products, and post fire regrowth of biomass burning are expressed in the spectra measured by AVIRIS. From the discipline research in ecology and vegetation, AVIRIS spectral images have been used to derive vegetation type, abundance and leaf water. These are critical parameters for predicting susceptibility to biomass burning. In the burning process, the fire emits electromagnetic radiation as a spectral function of temperature. This spectral signature has been used to derive both the temperature and area of burning fires with AVIRIS spectra (Green et al. 1996d). Smoke generated from biomass burning is of local to global importance with short and long term impacts on the environment. Properties of smoke and associated clouds have been derived from calibrated AVIRIS spectral images (Gao et al. 1993, Gao et al. 1995c). In the aftermath of biomass burning, the composition of the surface and regrowth may be measured and monitored with AVIRIS. In 1995, AVIRIS measured more than 1000 spectral images with many active fires during a deployment to Brazil. Research and analysis is continuing with these and other AVIRIS biomass burning data.

6.8 ENVIRONMENTAL HAZARDS

Spectral images measured by AVIRIS have been used to determine surface compositions that are directly or indirectly related to environmental hazards. For example, AVIRIS spectra were measured over the EPA superfund site at Leadville, CO. The spectra were used to map the distribution of acid generating minerals (Swayze et al. 1996). At Leadville, acidic water and mobilized heavy metals are an environmental hazard. The AVIRIS results at Leadville, both focused and accelerated the remediation at the site. AVIRIS spectra have been used to Assess the transport of hazardous mine waste down stream through alluvial processes (Farrand et al. 1995). For these applications, spectroscopy is required to accurately identify the specific mine related minerals and separate them from naturally occurring background minerals. The mineral of interest may be the hazard or an associated tracer. Imaging is required to uniformly sample the large regions that are involved in mining and alluvial transport of mine wastes. A natural hazard associated with the volcanoes of the Cascade mountains in the western United States has been investigated. AVIRIS spectral images were measured for most of these volcanoes. The spectra were used to map the distribution of specific alteration minerals. These alteration minerals are associated with weak zones in the volcanic slopes and are indicators of regions of instability and potential collapse (Crowley et al. 1997). As communities grow near these volcanoes, understanding the hazards is of increasing importance. As described in biomass burning, wild fires are another environmental hazard where AVIRIS spectral images provide information for assessing risk. AVIRIS has

applicability to environmental hazards where a link is established between the exposed surface composition and the human induced or natural hazard.

6.9 SATELLITE SIMULATION AND CALIBRATION

AVIRIS spectral measurements are ideal for the simulation and calibration of multispectral satellites that are currently operating or planned. AVIRIS has been used to simulate Landsat (Kalman et al. 1993) and EOS ASTER (Abrams 1992). In addition to simulation, AVIRIS spectral images have been used to investigate hypothesized spectral shifts in SPOT and AVHRR (Willart et al 1993, Wetzel 1995). An AVIRIS underflight of the optical sensor (OPS) on board the Japanese Environmental Resource Satellite (JERS-1) has been used to develop an improved on orbit calibration for this spaceborne sensor (Green et al. 1997). For on orbit calibration and validation objectives, AVIRIS has under flown the ADEOS satellite and plans are in place for a series of underflights of SeaWiFS and EOS sensors. The spectral, radiometric and geometric calibration achieved with AVIRIS to pursue research and applications is suited to validate, improve, and intercompare the calibration of satellite sensors on orbit. This is an important and growing role for AVIRIS with the planned launch of a range of satellite sensors measuring portions of the solar reflected spectrum.

6.10 COMMERCIAL APPLICATIONS

Commercial applications require value be obtained from the remotely sensed data. In remote sensing, value typically comes from decisions made from information derived from data. Imaging spectroscopy derives information from the molecular absorption features and scattering characteristics expressed in a range of materials on the Earth's surface. The spectral range, calibration and signal-to-noise of AVIRIS are well suited to derive information for commercial applications in mineral exploration (Kruse et al. 1996), mine waste cleanup, agricultural crop health and yield, land use (Ray et al. 1993), forest health and regrowth, coastal and wetland environmental status, wild fire risk assessment, urban planning, etc. A new thrust at NASA for commercial applications of imaging spectroscopy is expected to acquire a number AVIRIS data sets in pursuit of this objective.

6.11 SPECTRAL ALGORITHMS

Measurement of spectra as images by AVIRIS has lead to the development of a wide range of new algorithms to extract information from solar reflected spectra. To identify minerals with AVIRIS spectra algorithms have been developed to measure the position, depth, and shape of mineral absorption features (Clark et al. 1990, Clark et al. 1991). Expert system algorithms have been developed to determine material composition from AVIRIS spectra (Kruse et al. 1993). Algorithms to extract information have been developed based on the projection of AVIRIS spectra in high dimensional geometric space (Boardman 1993). Partial spectral mixture and multiple endmember mixture algorithms have evolved to take advantage of the subtle constituent information present in the AVIRIS spectra (Boardman et al. 1995, Roberts et al. 1996). Multivariate analysis (Johnson et al. 1994) and cross correlaogram spectral matching (Vandermeer et al. 1997) algorithms have been developed for vegetation and mineral objectives with AVIRIS spectral images. Classification algorithms have been developed to take advantage of the high spectral resolution of AVIRIS data (Hoffbeck et al. 1996). Algorithms continue to be developed to take advantage of the information embedded in the full AVIRIS spectrum.

Compression algorithms for AVIRIS spectra have been developed to explore reduction data volume and data rates (Roger et al. 1992, Roger et al. 1996ab, Ryan et al. 1997). Lossless compression has the advantage that subtle spectral absorption features embedded in the AVIRIS spectra are fully preserved. In contrast, the high compression rates of lossy compression must be evaluated in the context of the planned analysis algorithms for the specific objectives. Algorithms have also been developed to geocode AVIRIS spectral images based on the location and pointing of the sensor and the surface topography (Meyer 1994). Geocoding is of increasing importance as derived parameters from AVIRIS are used with other data sets for research and applications.

6.12 URBAN AND HUMAN INFRASTRUCTURE

The range of different molecular and scattering constituents found in the urban environment and associated with human infrastructure forms the basis for use of AVIRIS spectral images. A spectroscopic approach is essential to resolve the high spatial frequency mixed spectral signatures present. For example, the spectral characteristics of impervious surfaces are separable from mixtures of natural and vegetated surfaces in the urban environment (Ridd et al. 1992). An alternate urban application example is measurement of the composition of roofs in fire hazard zones. The spectral characteristics of communication and travel routes have been measured with AVIRIS spectral images (Salu 1995). The composition of the developed infrastructure as well as the disturbance of the natural background allowed detection and mapping of infrastructure elements. Imaging spectroscopy provides a uniform synoptic approach to mapping the surface material in the urban and adjacent environments to support characterization, monitoring, and planning.

6.13 MODELING

Models of the atmospheric and surface signatures measured by AVIRIS are essential to understanding and improving the measurements as well as deriving information from the spectra. An important model used with AVIRIS is the MODTRAN radiative transfer code (Berk et al. 1987, Anderson et al. 1995). This model has been used to validate and improve the calibration of AVIRIS through a series in flight calibration validation experiments. Comparison of MODTRAN predicted radiance with AVIRIS measured radiance has also resulted in improvements in the MODTRAN model. For example, discrepancies were found in the exoatmospheric solar irradiance spectrum used in MODTRAN version 2 (Gao et al. 1995). Small discrepancies currently exist in the modeling of the 1280 nm oxygen band in MODTRAN. MODTRAN is continuing to improve with recent enhancement of the cloud modeling capabilities (Berk et al. 1998). The ability of MODTRAN to accurately model the radiance spectra measured by AVIRIS allows MODTRAN to be used for model based inversion of parameters from AVIRIS spectra such as water vapor and surface reflectance. Other radiative transfer models have also been used to analyze and invert AVIRIS spectra (van den Bosch et al 1991).

Models of the surface are used to analyze and derive parameters from AVIRIS derived reflectance spectra. Leaf and canopy models have been used to investigate and extract vegetation parameters (Conel et al. 1993ab, Jacquemoud et al. 1995). Models parameterizing the absorption and scattering properties of water bodies have been used to predict the application of AVIRIS spectra to coastal and inland water research (Hoogenboom et al. 1998). Planck function based model of emitted radiance as a function of temperature has been used for analysis of AVIRIS spectra measured over fires and volcanic lava.

Models of the reflectance of snow as a function of grainsize have been used to derive snow properties from AVIRIS spectra. Accurate models of the absorption and scattering properties of surface materials provide an important analysis and inversion approach for extraction information from calibrated AVIRIS spectra.

7.0 CONCLUSION

Ground based spectroscopy has been increasingly used for research and applications across a range of research and applications areas. AVIRIS was developed to extend the use of spectroscopy to the realm of Earth remote sensing. AVIRIS was the first imaging spectrometer to measure the solar reflected spectrum from 400 to 2500 nm with contiguous 10 nm channels. The AVIRIS system was designed, developed, upgraded, and maintained to support a range of NASA research and applications objectives. The initial design of the sensor with an efficient scan mirror, f/1 spectrometers and 200 micron detectors enabled a series of upgrades that resulted in high signal and low noise performance. A parallel set of upgrades focused on stabilizing the spectrometers and onboard calibrator as well as developing a set of new spectral, radiometric and spatial calibration techniques. In combination, these efforts resulted in the current accurate spectral, radiometric and spatial calibration as well as high signal-to-noise of AVIRIS. With the increased demand for AVIRIS spectral images, the data system was upgraded to take advantage of new computer and mass storage technology. This upgrade also resulted in the breakup of the monolithic AVIRIS processing program into a series of simple program modules dedicated to the calibration and distribution each years data. As the sensor, calibration and data system evolved, the flight operations procedures and technology were improved. These procedures ensure that AVIRIS acquires the research and application data sets requested by the investigator and that the AVIRIS sensor is performing nominally before, during, and after each flight. Both email and the AVIRIS website now play an important role in keeping investigators informed of acquisition and performance status. The upgrades to the sensor, calibration, data system and flight operations leave AVIRIS in a strong position to continue to support research and application through the future.

The initial science objectives for AVIRIS were investigation of the vegetation red edge and mineral absorptions in 2200 nm spectral region. With the measurement of the solar reflected spectrum from 400 to 2500 nm at high spectral resolution and improved performance, investigations using AVIRIS are increasing in number, diversity, and rigor with each year of data acquisition. The high signal-to-noise and accurate calibration of AVIRIS spectral images are relevant to the full range of investigations where molecular absorptions and scattering signatures are expressed in the solar reflected spectrum.

Future spaceborne satellite sensors will measure solar reflected spectra as images in the manner established by AVIRIS. These sensors will provide access to spectral images from all regions of the Earth with multi temporal coverage. However, the altitude and velocity of satellites cause significant challenges to measure high quality spectra from space. Accurate spectral, radiometric and spatial calibration of this first generation of spaceborne imaging spectrometer will be difficult and require new approaches and capabilities. The end-to-end AVIRIS system will continue to be required measure high quality spectral images for research and applications as well as to validate this first generation and spaceborne imaging spectrometers.

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FIGURE CAPTIONS

Figure 1. The concept of imaging spectroscopy is shown with a spectrum measured for each spatial element in a image and the spectrum is analyzed for science research and applications in a range of disciplines.

Figure 2. The 224 spectral channels of AVIRIS are shown with a transmittance spectrum of the atmosphere as well as the 6 solar reflected bands of the Landsat Thematic Mapper.

Figure 3. A depiction of the AVIRIS sensor is shown with the major subsystem used to acquire spectral images of the Earth's land, water and atmosphere environments.

Figure 4. A 1.0 nm spectral resolution modeled upwelling spectral radiance is given for the Ivanpah Playa, CA calibration target in 1997.

Figure 5. Digitized AVIRIS signal from the calibration target on Ivanpah Playa, CA is shown as well as the average dark signal measured in the non imaging portion of the crosstrack scan.

Figure 6. The high, two spectral and dark signals measured from the AVIRIS onboard calibrator are shown for the beginning of the flight line at Ivanpah Playa, CA 1997.

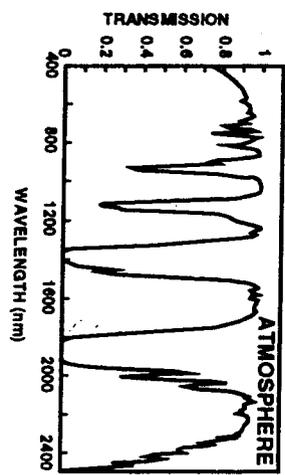
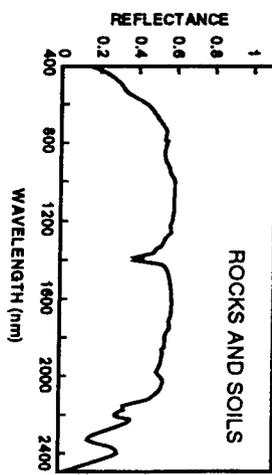
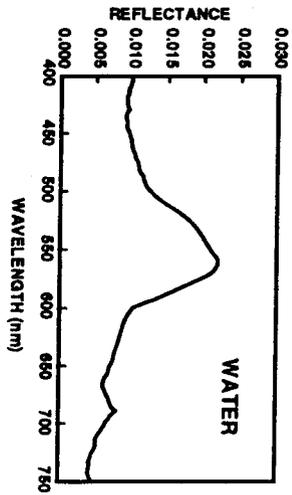
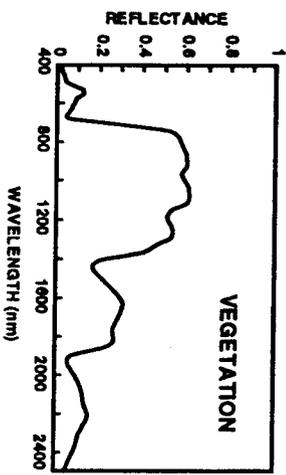
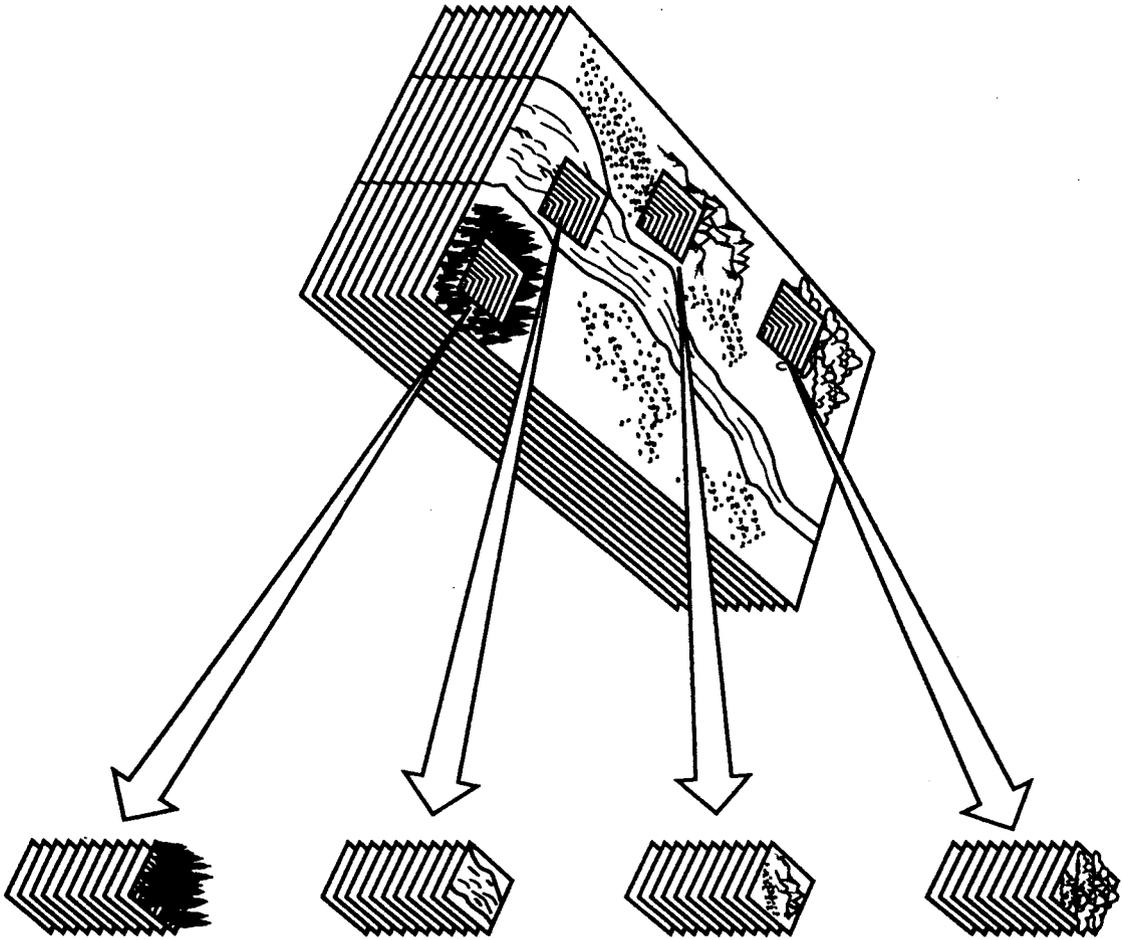
Figure 7. AVIRIS 1997 spectral channel positions and the full width at half maximum response are shown as well as the calculated uncertainties.

Figure 8. AVIRIS radiometric calibration coefficients and uncertainties are shown for the 1997 flight season.

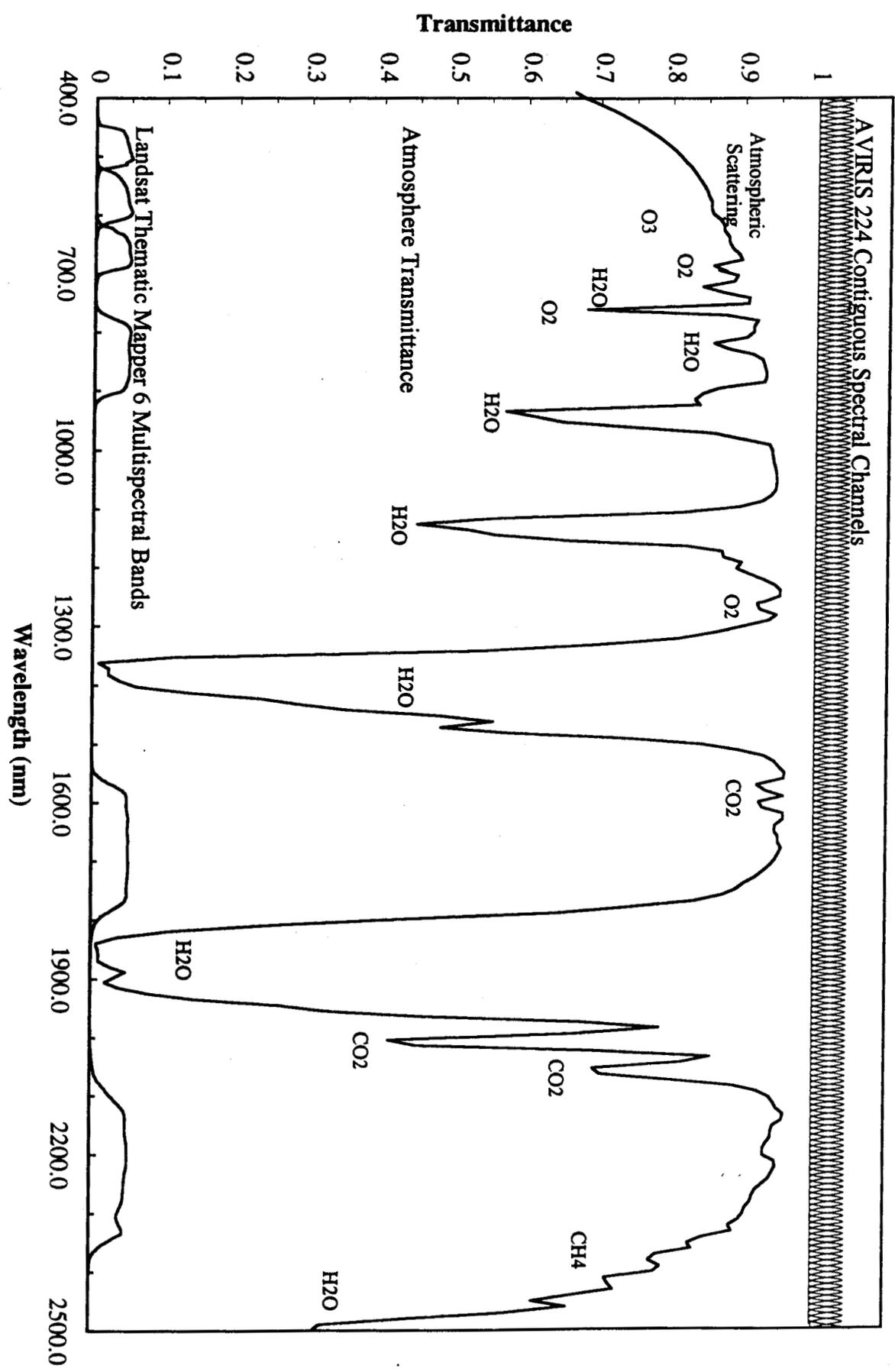
Figure 9. AVIRIS signal-to-noise for 1997, 1994 and 1987 is shown for the reference radiance.

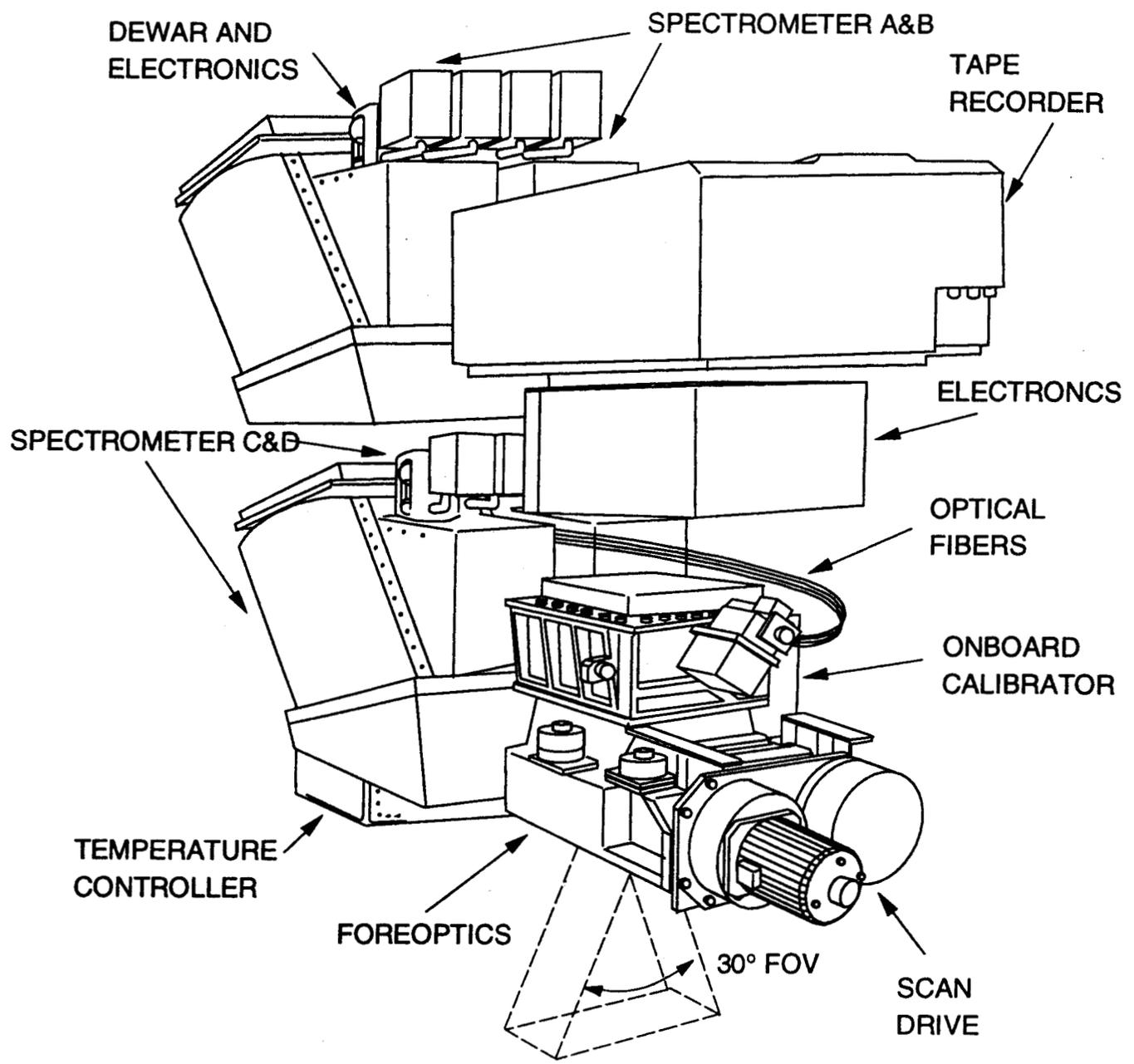
Figure 10. AVIRIS spatial response functions from a portion of the field of view are shown. The sampling is nominally 0.9 milliradians and full width at half maximum is 1.0 milliradians.

Figure 11. AVIRIS in flight calibration validation result is shown for 1997. The agreement between the MODTRAN predicted radiance and AVIRIS measured radiance for the calibration target is better than 96 percent.

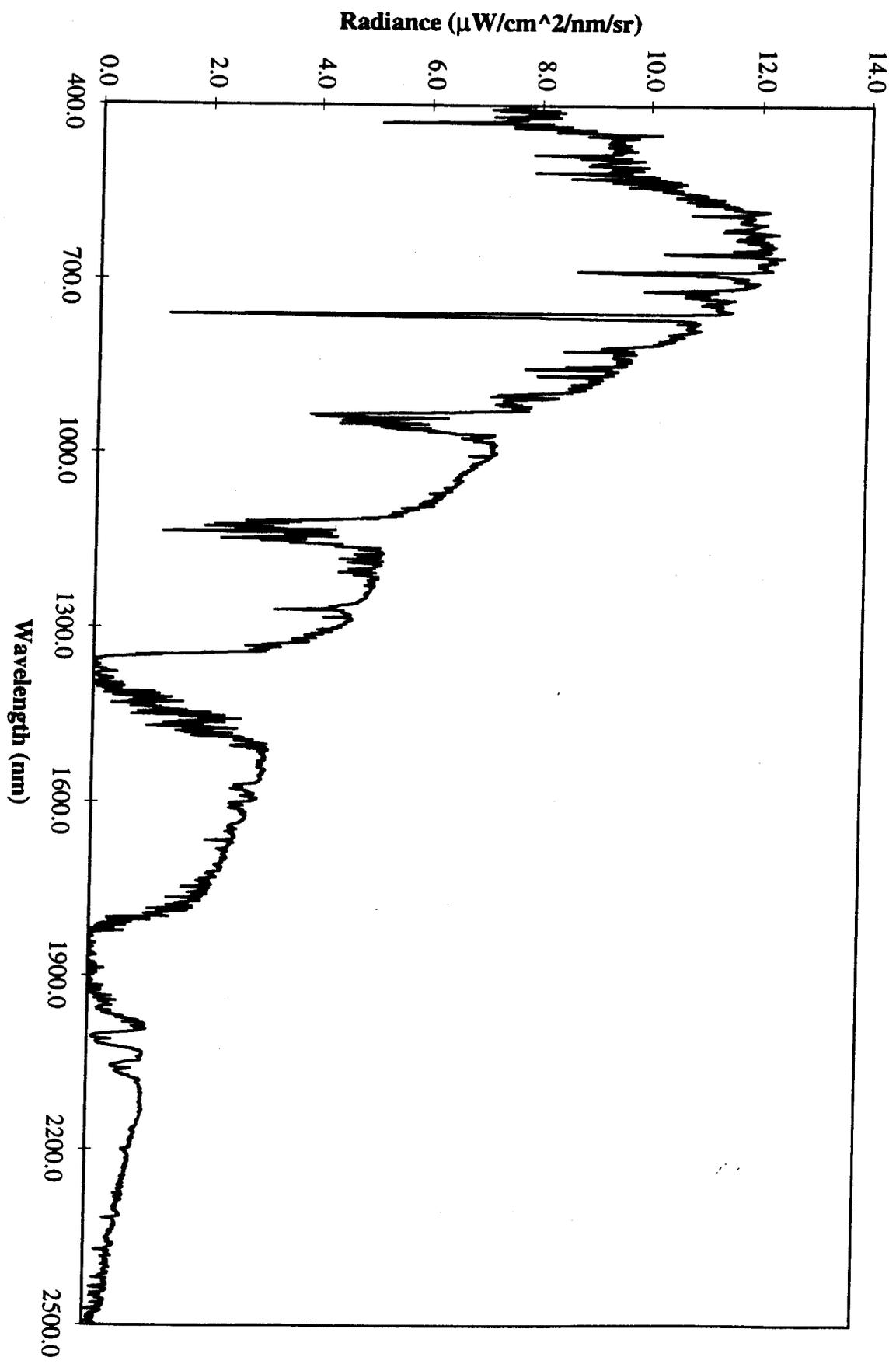


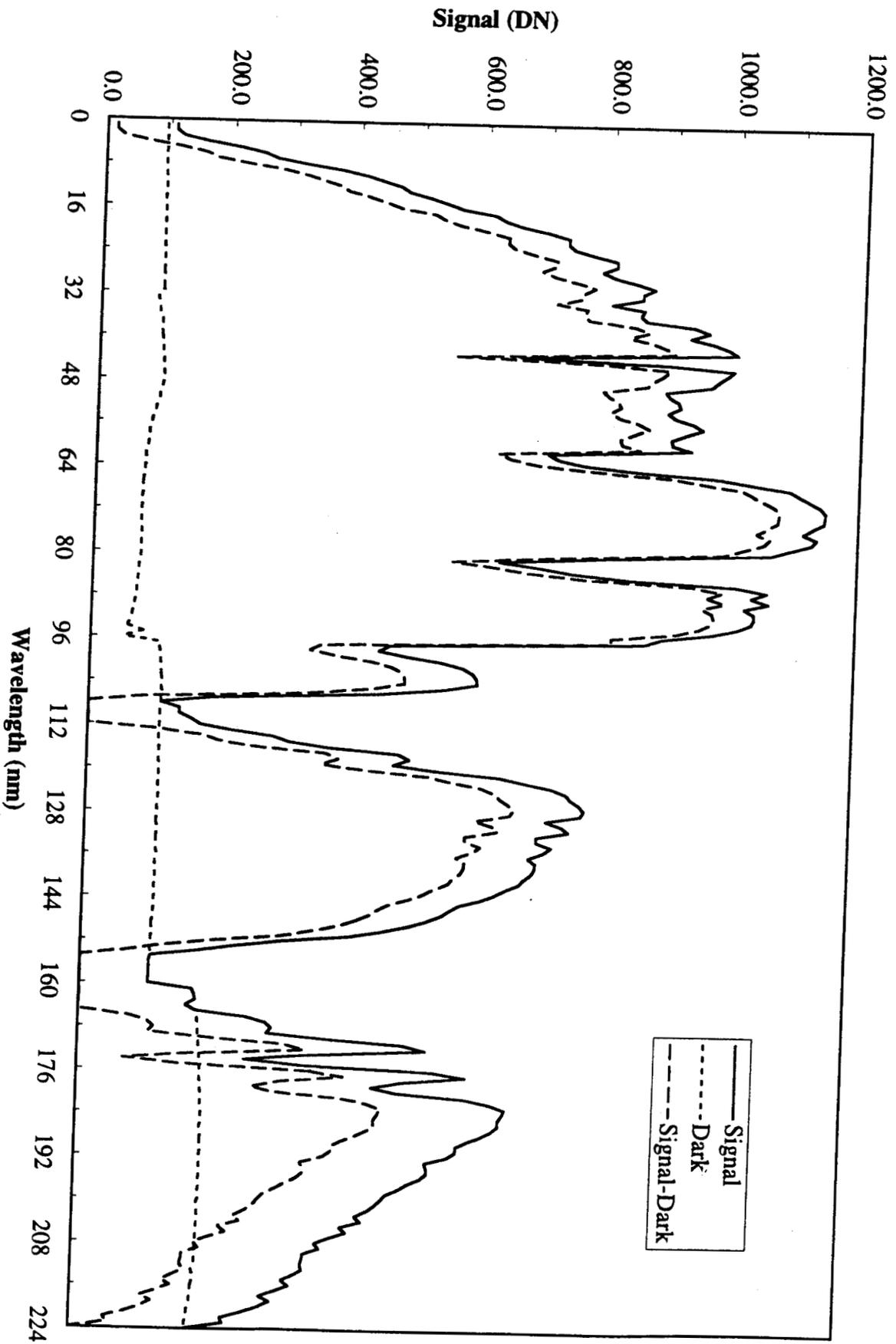
205
Fig 1

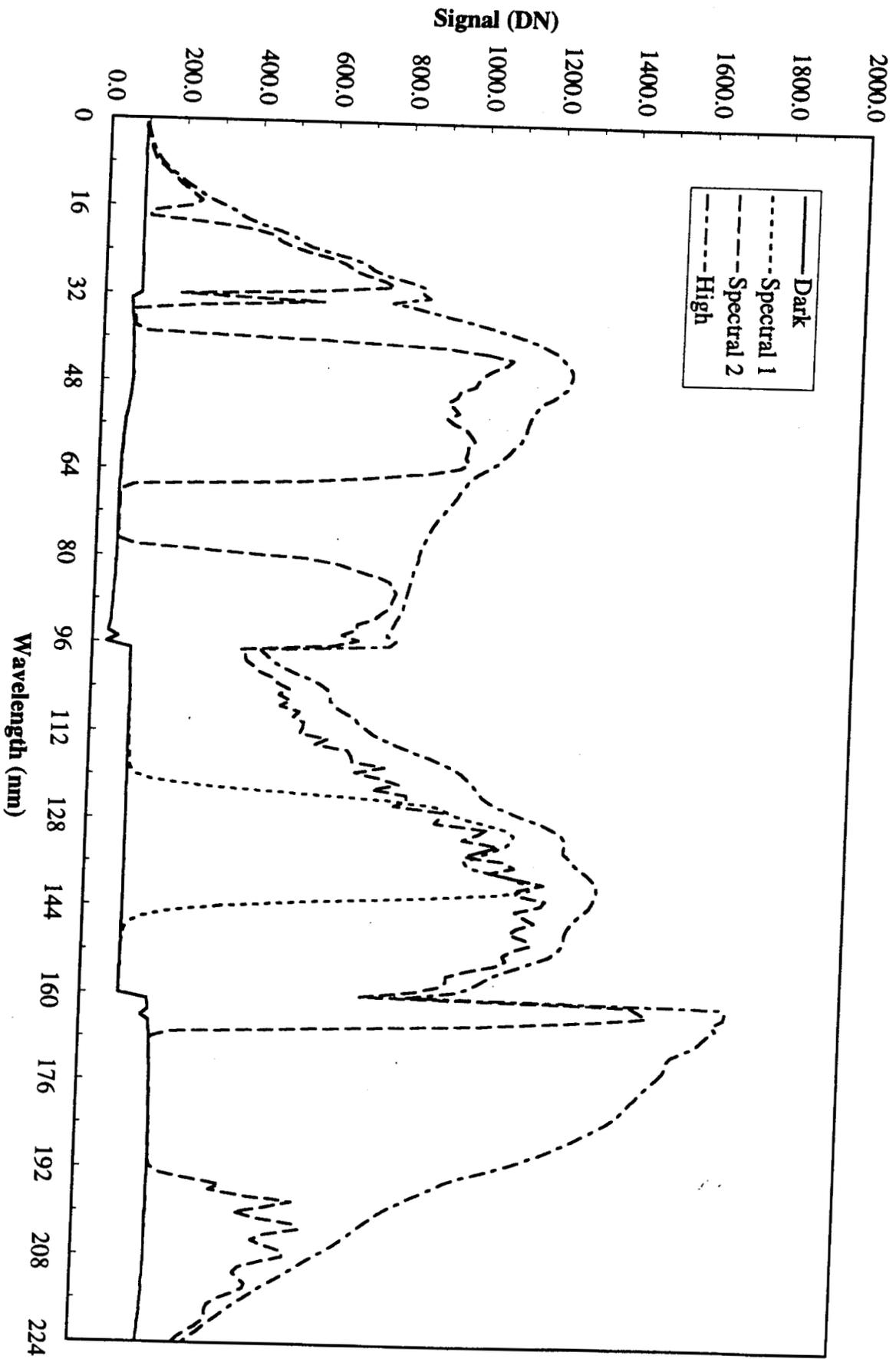




POG FIG 4

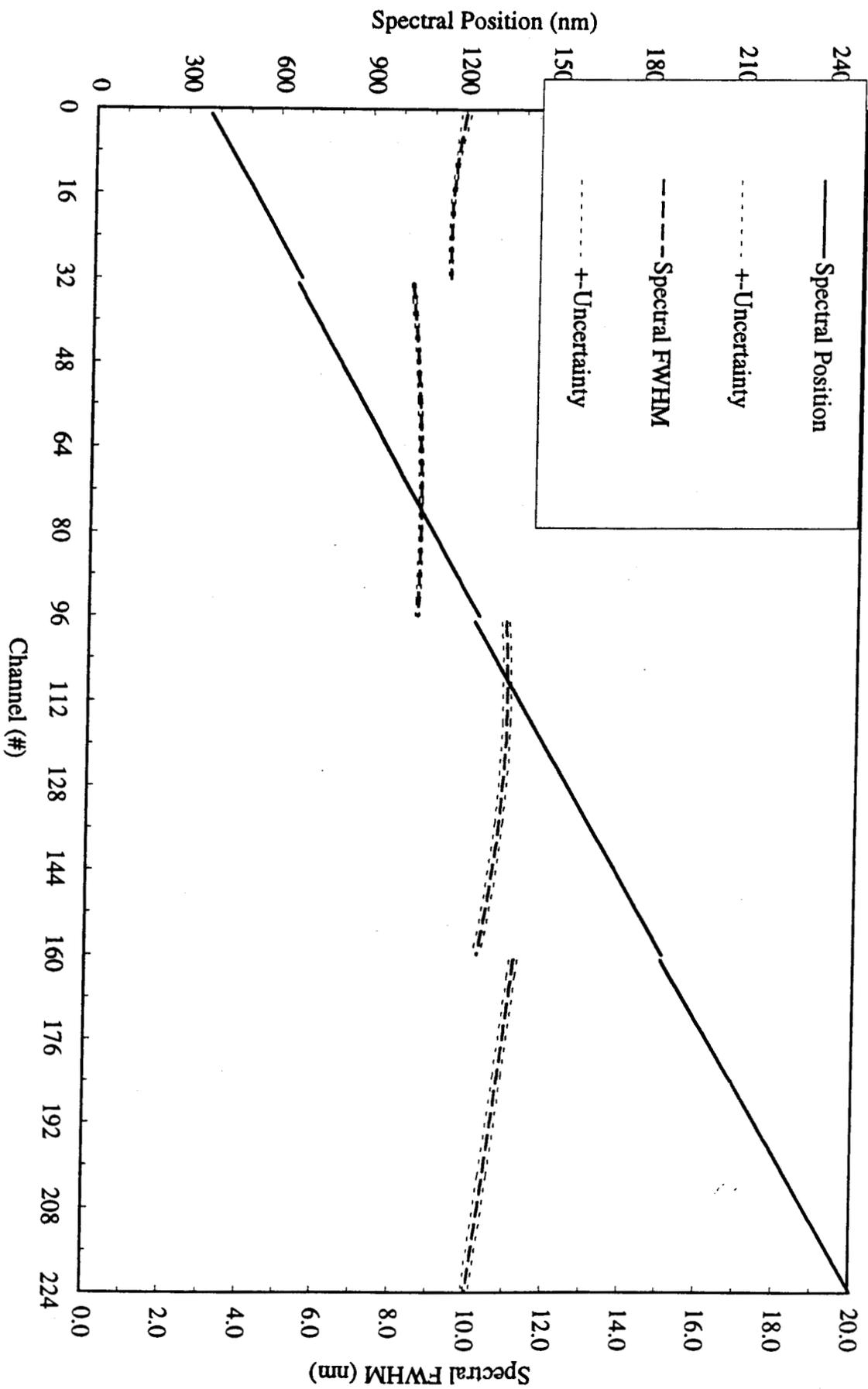




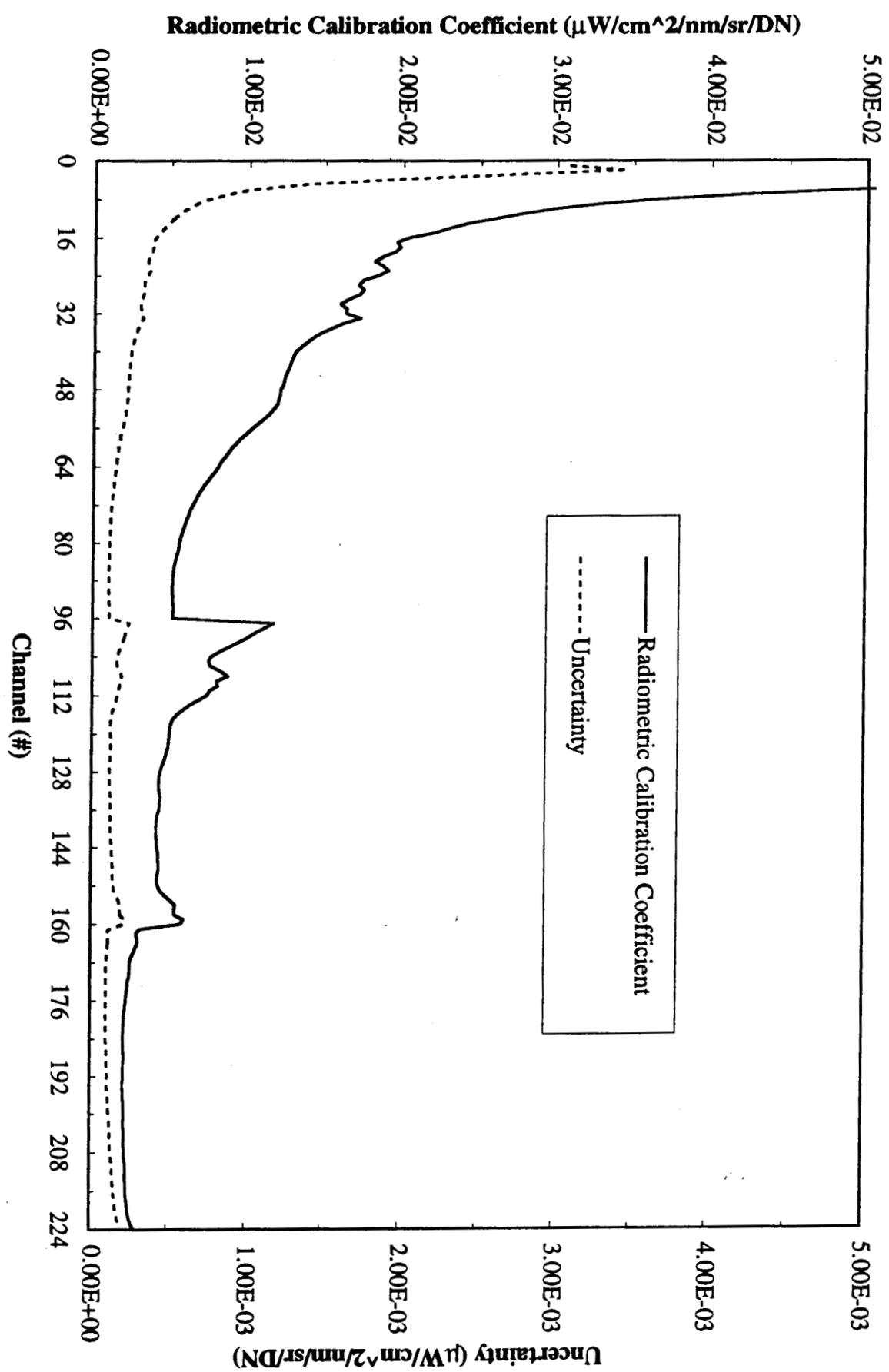


Page Fig 6

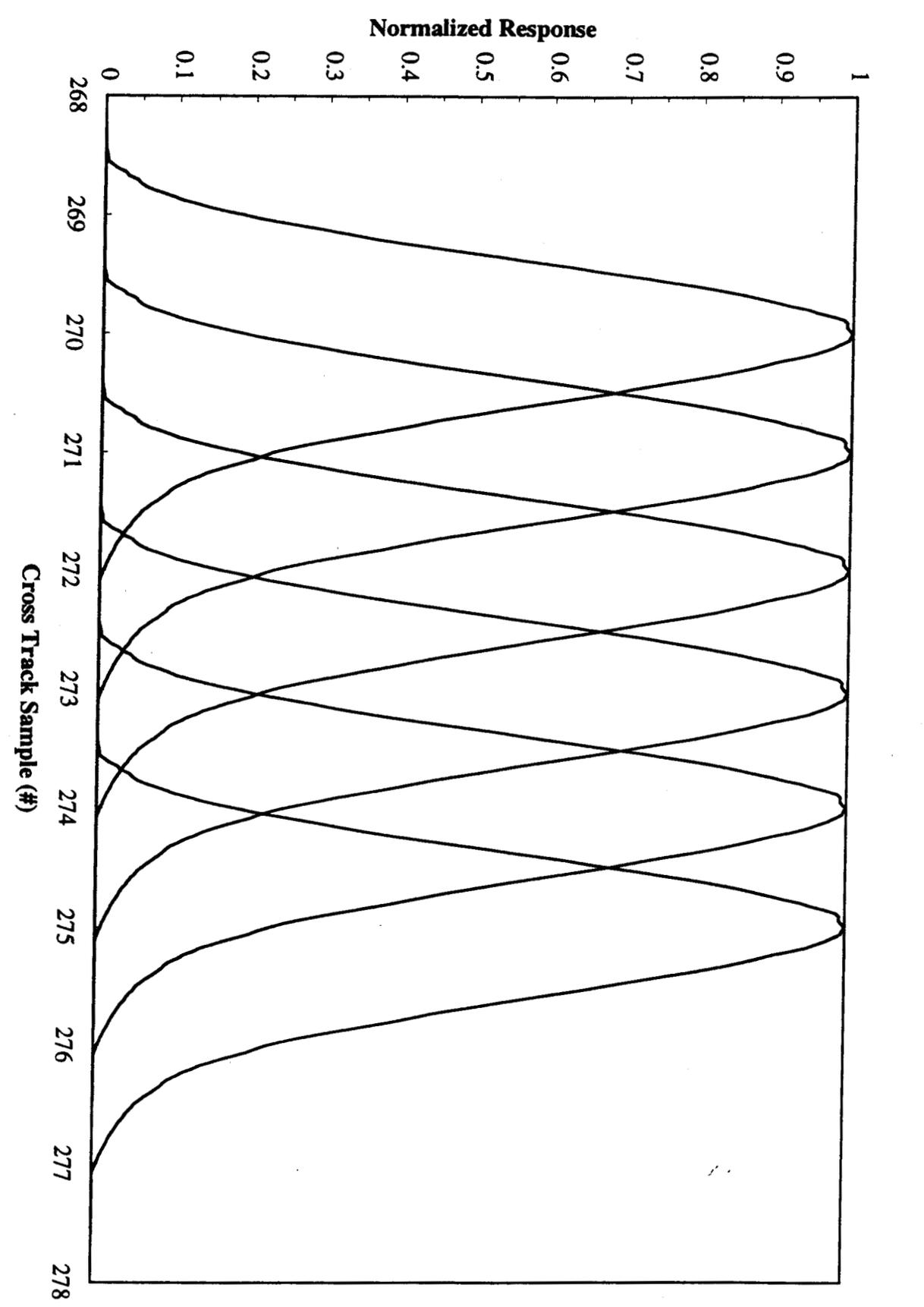
POG Fib 7

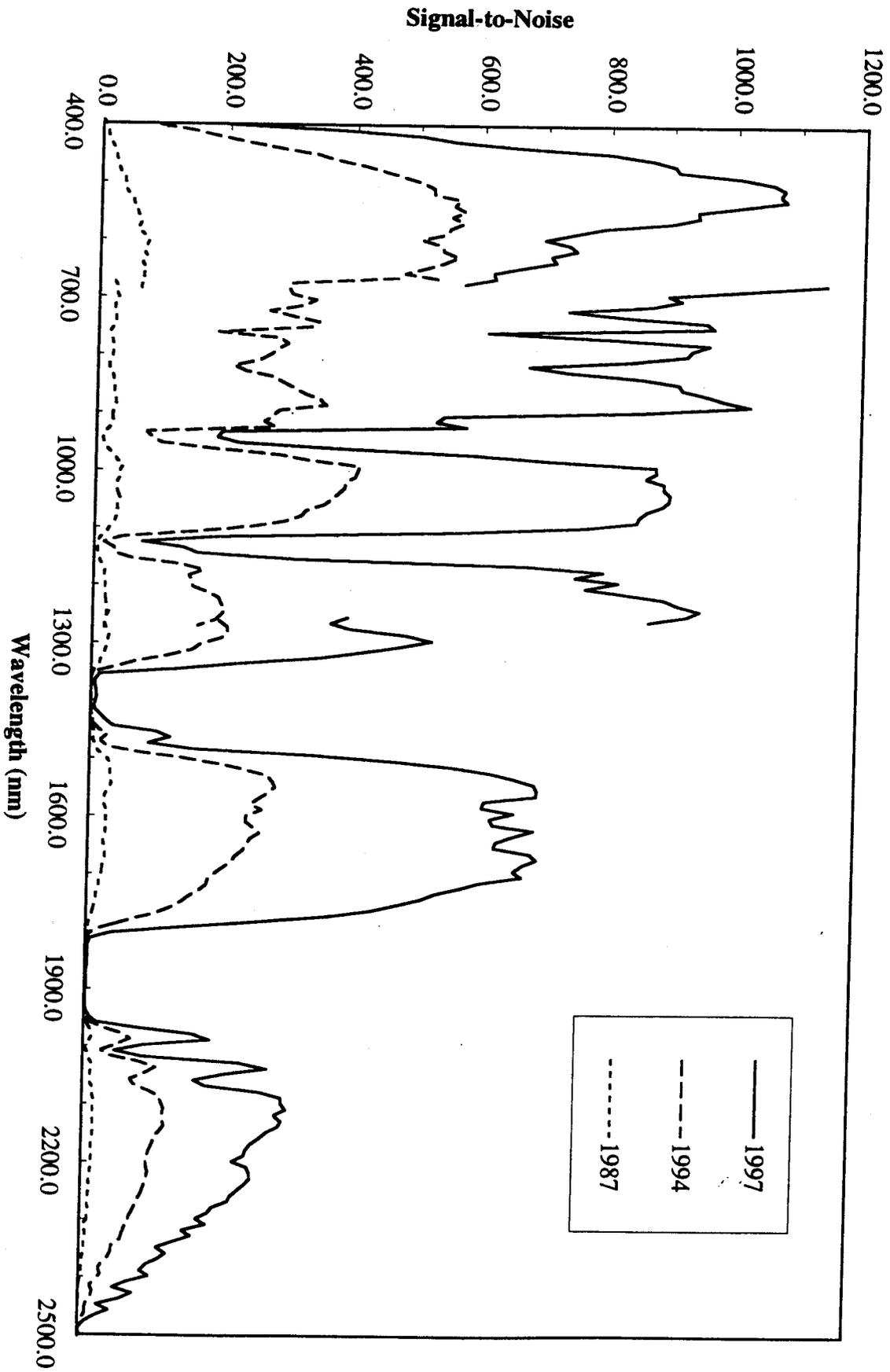


P05 FIG 8



206-FIG 9





TABLES

Table 1. AVIRIS sensor characteristics.

Imager type	Whiskbroom scanner
Scan rate	12 hertz
Dispersion	Four grating spectrometers (A,B,C,D)
Detectors	224 detectors (32,64,64,64) Si and InSb
Digitization	12 bits
Data rate	20.4 mbits/second
Spectrum rate	7300 spectra/second
Data capacity	>10 gigabytes (>8,000 km ²)

Table 2. AVIRIS data characteristics

SPECTRAL

Wavelength range	400 to 2500 nm
Sampling	<10 nm
Spectral response (fwhm)	10 nm nominal
Calibration	<1nm

RADIOMETRIC

Radiometric range	0 to maximum lambertian radiance
Sampling	~ 1 dn noise rms
Absolute calibration	>= 96 %
Inter flight stability	>= 98 %
Signal-to-Noise	Exceeding requirement
Polarization Sensitivity	<= 1%

GEOMETRIC (at 20 km altitude)

Field of view	30 degrees (11 km)
Instantaneous FOV	1.0 mrad (20 m)
Calibration	<=0.1 mrad
Flight line length	800 km total

Table 4. Nominal ER-2 aircraft characteristics for AVIRIS.

Aircraft	NASA ER-2
Altitude	20 km
Velocity	730 km/h
Range	2100km
Flight duration	6.5 hours
Launch sites	Domestic & foreign
